Journal of Forestry Research (2014) 25(2): 237−248
DOI 10.1007/s11676-014-0455-0

REVIEW ARTICLE

The coppice-with-standards silvicultural system as applied to *Eucalyptus* plantations - a review

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Received: 2013-05-21; Accepted: 2013-06-28

Abstract: We review the management of *Eucalyptus* species under a coppice-with-standards (CWS) silvicultural system. CWS management results in product diversification, permitting production of small and large scale timber from the same stand. *Eucalyptus* species are suitable candidates for CWS management because: there are large worldwide plantation areas, sprouting capacity is high, and eucalypts are multipurpose species. We discuss (1) short rotation *Eucalyptus* coppice management for energy and pulping and (2) *Eucalyptus* seedling management for solid wood products. We review the literature and discuss experiences with *Eucalyptus* managed under the CWS system. We also assess projects dealing with *Eucalyptus* coppice management, stand density regulation, pruning, and stand and wood quality. The growth environment of the standard trees (heavy competition up to the first harvest, free growth afterwards) coupled with long rotations (>20 years) results in high quality logs for solid wood products. Early pruning should be applied to enhance wood quality. We propose a system for the silvicultural management of *Eucalyptus* under the CWS system, elaborating on the consequences of initial planting density, site productivity, and standard tree densities as well as timing of basic silvicultural applications.

Project funding: This work was suported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), through the PSDE program, process number BEX: 2939/12-6.

The online version is available at http://www.springerlink.com

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Keywords: stand density regulation, coppice management, pruning, silvicultural system, stand production diversification, CWS

Introduction

Coppice-with-standards (CWS) is a silvicultural system that has been applied in European forest management since the Middle Ages. This system involves managing a low density of seedling trees as an overstory for one or more cycles of coppiced understory. This CWS system enables the production of small diameter wood for energy or pulping purposes as well as large dimension timber for solid wood products.

The use of a forest stand to produce multiple products represents a potentially competitive advantage for forest landowners, aggregating flexibility in product commercialization and thereby reducing risks of financial loss (Soares et al. 2003). In this context, it is desirable to develop silvicultural management regimes that can enhance production of multiple products. The CWS silvicultural system is ideal to promote diversification of forest wood products. The use of *Eucalyptus* for energy and pulping purposes is consolidated, and as reported by Montagu et al. (2003), all commercially grown *Eucalyptus* species are capable of producing solid wood products if appropriately managed (mainly by pruning and thinning).

Eucalyptus plantations are distributed worldwide and are destined for the production of several goods, such as: charcoal, pulp and paper, construction timber, firewood, honey, essential oil, ornamental, and solid wood products. Currently there are about 20 million hectares of *Eucalyptus* plantations worldwide, of which about 50% are located in India, Brazil and China (Iglesias-Trabado and Wilstermann 2008). The wide geographic distribution of eucalypt cultivation can be attributed to: its fast growth (values of up to 83 m^3/ha/year at age six years have been reported by Stape et al. 2010), many species coppice readily, it is a multi-purpose species, it allows a high level of genetic improvement, and fulfills demand in consolidated markets.

Most of the world's *Eucalyptus* forests are managed for pulp and energy, and are characterized by high planting densities, few silvicultural interventions after establishment, and short rotation periods. Of 113 million m^3 of *Eucalyptus* wood harvested from Brazilian plantations in 2010, 45% went to cellulose and paper production, 45% to industrial firewood and charcoal, and 9% to solid wood products (ABRAF 2012).

Eucalypts are appropriate candidates for management by the CWS system because many species present good sprouting capacity and are suitable for solid wood products. Reynders (1984) deemed the CWS system to be the most appropriate management system for eucalypt plantations established to fulfill the needs of rural communities in developing countries. Thus, management of eucalypts under CWS is very promising for small and medium scale private forest landowners.

There are many prerequisites for successful management of a stand through the CWS system. These include: successful regeneration through coppice shoots; ability to respond with rapid growth once the canopy is opened; stand resistance to abrupt canopy opening; and wood quality response to growing conditions. This review describes how eucalypts meet these prerequisites when managed under a CWS system. We describe experiences gained from eucalypt management under the CWS system and we draw inferences drawn on best practices for pruning, thinning, and coppice studies.

Characterization and application of the CWS system

Troup (1928) defined the CWS system as consisting of two distinct elements: (1) a lower even-aged story treated as simple coppice, and (2) an upper story of standards forming an uneven-aged crop and treated as high forest on the principle of the selection system. Troup (1928) also defined a variation of the CWS and named it "coppice of two rotations". The coppice of two rotations is a simpler system than the traditional CWS, since the standards are not managed by the selection system and, as such, form an even-aged crop. The management of a stand by the coppice of two rotations system will result in a two layered forest, composed by coppice shoots in the understory and standards in the overstory.

The CWS system has been applied in Europe since the Middle Ages, dating from the 7th century in Germany and from the 12th century in England. In 1544 a series of statutes for the preservation of woods was applied in England, including, among others, management schemes to be followed by tree owners. Concerning coppice woods, it was required that a minimum of 30 standard trees be retained per hectare (Troup 1928). About 11 thousand hectares of *Quercus* spp. are still managed using the CWS system in England (Forestry Commission 2003).

The CWS system in France was developed for the management of the royal forests between 1664 and 1683 (Machar 2009). A three-fold objective was set for the management of the king's forests: (1) production of standard oak timber for construction of buildings and naval vessels, (2) production of firewood and charcoal, (3) pig foraging on acorns from the mature oaks of the top stand layer.

The CWS system was once very important in Europe, in such countries as France and England, and in Central Europe. Up to 1920, one third of all French forests were managed by the CWS system (Stewart 1980). At beginning of the 20th century 3% of the current territory of the Czech Republic (60,000 ha) was managed by the CWS system (Machar 2009). Coppice systems eventually lost importance in European countries, mainly due to the rise of mineral coal use for energy. This reduced the value of firewood and small scale timber, culminating in the conversion of many simple coppice and CWS stands to high forest.

The CWS system is also applied in other parts of the world. In India the species *Tectona grandis* and *Shorea robusta* are grown as standards, while in Korea timber species are grown as standards over coppiced leguminous species for firewood coppice (Stewart 1980). The CWS system preserves 10 to 20 tree species as standards in Indian forests (Bebarata 2006). In Nepal some *Shorea robusta* stands are managed by the CWS system, with standards covering 25% to 50% of the canopy cover and the coppice understory cut every seven years (Department of Forest Research and Survey 2009).

During colonial times in southern Africa, some native species (*Baikiaea plurijuga*, *Pterocarpus angolensis*, and *Marquesia macrourasob*) were managed under the CWS system by British and Belgium forest managers. The system was also used for the management of African miombo formations, with the removal of the coppice material every 40 years and harvest of the standards every 60 to 100 years (Bellefontaine et al. 2000).

The CWS system is used in the tropics, but there is little information about the areas involved (Matthews 1991). There is little experience with *Eucalyptus* under CWS management. Some trials have been established under this system in Africa with *E. grandis*, *E. saligna*, and *E. maidenii* (Poynton 1983; Reynders 1984). In Brazil trials have been undertaken with *E. grandis* and *E. saligna* (Inoue and Stöhr 1991; Spina-França 1989).

Coppice in *Eucalyptus*

Eucalypts exhibit rapid coppice regrowth following felling or defoliation. This is attributed to the presence of epicormic buds as well as lignotubers situated in the live bark and cambium near the root and stem junction point (Little and Gardner 2003, Reis and Reis 1997).

Eucalyptus coppice management is common worldwide, and is used to manage plantations that produce wood for the pulp and biomass industries. The number of coppice cycles before beginning a new rotation (e.g. replanting the stand) depends mainly upon sustained wood production of the coppice cycles. For instance, Brazilian *Eucalyptus* coppice management historically consisted of a three cycle rotation, one high forest clear cut followed by two coppice clear cuts (Souza et al. 2001). Recent studies have shown that a two cycle rotation is more profitable considering the higher productivity of current *Eucalyptus* genetic material and lower establishment costs (Rezende et al. 2005).

The current silvicultural technology used in the coppice management of Brazilian *Eucalyptus* forests (minimum cultivation methods, high fertilizer rates) guarantees wood production volumes in the second rotation very similar to those of the first rotation (Gonçalves et al. 2008).

The decision whether to regenerate a stand from coppice or to plant seedlings is most often economic. Among the factors that influence the decision to replant the stand are: productivity of the coppice crop, availability of genetically superior planting material, and the number and length of the coppice rotations (Nobre and Rodriguez 2001, Whittock et al. 2004). Since the regeneration of a coppiced stand requires less intensive silvicultural interventions than replanting, a coppiced stand can be the most economical option even if its productivity is lower than that from a high forest stand. For instance, studies conducted in the savanna region of Brazil have shown that *Eucalyptus* coppice management is an economically viable option even if productivity is 70% of that from the original high forest stand (Guedes et al. 2011).

Not all *Eucalyptus* species can be managed as coppice stands, either because of low sprouting capacity, low vitality of the coppice stems causing failure to obtain commercial dimensions, or fungal damage where the coppice attaches to the stump (Abbott and Loneragan 1982, Geldres et al. 2004). *Eucalyptus* species of the subgenus *Symphyomyrtus* (such as *E. camaldulensis*, *E. grandis* and *E. globulus*) generally exhibit high sprouting capacity. On the other hand, *Eucalyptus* species of the subgenus *Monocalyptus* (such as *E. fastigata*, *E. pilularis* and *E. fraxinoides*) tend to exhibit more variable sprouting capacity (Higa and Sturion 1997, Sims et al. 1999).

Besides species, there are many different factors that influence the successful management of a coppice regenerated stand (Table 1). Operational factors that can readily be controlled by silvicultural interventions include: stump height after tree felling, number of sprouts per stump, harvest residue cleaning around the stumps, and weed control. With higher stumps a greater number of epicormic buds and lignotubers remain, increasing the probability of sprouting (Stape et al. 1993). *Eucalyptus* coppice is normally cut at a maximum height of 12 cm, the stool being given a sloping surface to prevent water from settling (Matthews 1991).

The abundant regeneration of sprouts per stump can either be managed by thinning to one, two, or three sprouts per stump for harvest in later years or with no thinning but harvest during earlier years for biomass. A stump thinning operation reduces growth competition between sprouts, which can result in more vigorous growth for the remaining sprouts. Souza et al. (2012) found that out of eight different *Eucalyptus* clones in a Brazilian site (cut at age 13 months and tested for stump thinning down to two stems per stump 9 months after cutting), three responded with greater diameter growth, while the rest presented greater but not statistically different values when compared to unthinned stumps. Geldres et al. (2004) recommended that for coppice management of *E. globulus* and *E. viminalis* in Chilean sites, stump thinning to three sprouts should be conducted 18 months after harvest if the intended use is pulp or firewood. For sawn wood the thinning should be down to one or two sprouts per stump.

Table 1: Example of influential factors determining successful *Eucalyptus* coppice management grouped per conditioning factors and sprouting phase, adapted from Stape (1997)

Conditioning factor	Sprouting phase	Influential factors
Genetic	Sprouting	Species/Provenance/Clone
		Hydraulic stress
		Nutritional stress
Operational	Establishment	Stump height
		Ant and termite control
		Stump shading
		Harvest damage
		Sprout density per stump
Environmental	Growth	Thermal regime
		Water Resources
		Soil and Physiographic condition
		Fertilization/irrigation
		Weed control

Stump mortality may occur if harvest residue impedes direct sunlight incidence or if the stumps are damaged during timber harvest and forwarding operations. Camargo et al. (1997) reported 8% higher stump mortality among stumps of *E. grandis* that were shaded by harvest residue. Machado et al. (1990) found stump mortality of about 15% for *E. alba* stumps damaged during a wood forwarding operation. Both authors reported sprout height growth reduction for shaded and damaged stumps.

Stand density regulation and growth response

When managed under the CWS system, the growth space of the standard trees experience three distinct phases: closed canopy stand at the high forest stage; very large canopy opening after the first cut; and competition from the understory once the coppice component is established. Due to competition from neighbors, diameter growth restriction of the standard trees occurs during the first growth phase. However, certain benefits can arise in growing denser stands, including abundant trees for standard tree selection, reduced branch size, improved tree form, and suppression of weeds (Neilsen and Gerrand 1999, Pinkard and Neilsen 2003, Forrester et al. 2010).

In a CWS system, the first cut of the stand will occur when the trees attain commercial dimensions (five to seven years for fast growing sites). The initial resource competition between trees before the initial cut precludes the high diameter growth rates that *Eucalyptus* typically exhibit during young ages. Nutto et al. (2006) estimated that growth rates of up to 6 cm per year are possible for *E. grandis* during the first 3.5 years of age for stands planted at low densities. On sites of high quality, annual growth rates of up to 4 cm are possible at later ages if low stand density is maintained (*ibid*.).

Thinning at later ages (7−10 years) has smaller positive effects on final crop tree growth than does early age thinning (2.7-3.5 years, Forrester and Baker 2012). Thinning later can result in smaller thinning responses because younger trees have greater ability to expand their crowns in response to the extra space than do older eucalypt trees. Even if trees respond similarly to early or late thinning, trees will be smaller following late thinning because the trees have been growing in dense stands with more intense resource competition. Thinning early also makes use of the higher light-use efficiency of dominant trees in relation to non-dominant trees (Campoe et al. 2013). The disadvantages of thinning later in a CWS system can be offset by longer harvest rotations for standard trees and by planting at densities lower than those used for typical thinning regimes (i.e. 100 to 400 final crop trees/ha).

The competition imposed by the coppice understory has varying impacts on standard tree growth. Connell et al. (2004) reported that 6 years after the removal of coppice competition from a thinned stand of *Eucalyptus sieberi* (stand age 28 years, thinned to about 250 trees/ha) basal area growth of potential sawlogs (largest 150 trees/ha) increased by 19% over that of trees in thinned-only forest. Forrester et al. (2012) reported that the removal of coppice competition resulted in basal area increase for the sawlog trees of an *E. globulus* stand thinned from 850 to 400 trees/ha but no increase was detected after the removal of coppice competition from an *E. tricarpa* stand thinned from 600 to 100 trees/ha. Thus, the response of standard trees to the coppice competition might be linked to the density of the remaining trees, with lower densities resulting in less competition. The small density of standard trees that will be retained in the stand in a CWS system might ameliorate the competition imposed by the coppice understory.

If very low densities of standard trees are left after the first cut (e.g. densities lower than 50 trees/ha), and enough time is given for the trees to grow (e.g. rotations of 21 years or longer), very large diameter trees can be obtained from the CWS system. Nutto et al. (2006) estimated that on a site of higher quality (mean diameter increment of 3.6 cm/year), trees of average diameter of 54.5 cm would be possible in a 15 year rotation for *E. grandis*, with thinning regimes starting at 5 years and final densities of 115 trees/ha. A similar target diameter of 54.6 cm was considered possible for *E. globulus* planted in the Iberian Peninsula in a 31 year rotation, with thinnings starting at age 6 and a final density of 100 trees/ha (Nutto and Touza Vázquez 2004).

Stem form and wind resistance

During the first growth phase of the standard trees the lateral restriction from neighbors will accelerate live crown height rise. A more cylindrical stem results from this initial competition for light, since proportionally more assimilates are allocated in or near the live crown height than in other stem sections (Larson 1963). For instance, Maestri (2003) reported stem taper values of 1.6, 1.1 and 0.7 cm/m between stem heights of 1.3 and 4.15 m for ten year old *Eucalyptus* sp. trees grown in densities of 250, 450 and 1111 trees/ha, respectively. The author attributed this variation in stem taper to the lower green crown height of lower density stands.

The competition for light in stands grown at high densities prioritizes height growth over diameter growth. This means that after the first cut, residual trees will have high slenderness values, as characterized by the height/diameter ratio. Slenderness ratios higher than 100 m/m are associated with less wind resistant trees (Wood et al. 2008).

Unless open-grown, *Eucalyptus* trees tend to exhibit high slenderness values. For example, Warren et al. (2009) reported that mean slenderness ratios for three *Eucalyptus* species at age six years ranged from 90 to 114 m/m for planting densities of 714 and 3333 trees/ha, respectively. The authors also identified that planting densities over 1250 trees/ha resulted in mean slenderness values equal to or greater than 100 m/m.

Thinning operations results in increased exposure of retained trees to wind and increasing risk of windthrow (Fagg 2006). Thus, the abrupt opening of a stand after the first harvest, coupled with the high slenderness values of the standard trees, makes wind damage to the residual stand a possibility on sites prone to strong winds. The dispersed nature of the standard trees also increases the probability of wind damage (de Montigny 2004).

The small crowns of the standard trees after stand opening is a factor that can reduce the probability of wind damage by reducing wind penetration and sail area of small crowns (Rowan et al. 2003; Wood et al. 2008). Accelerated diameter growth of standard trees after the first harvest will reduce slenderness ratios, thereby increasing wind resistance over time. For Australian *Eucalyptus* forests, a recovery time of 2 to 5 years is considered adequate for stands to regain wind resistance after thinning (Wood et al. 2008).

Wood quality implications

Wood quality of standard trees may benefit from management in a CWS system in three different ways: higher basic density values, lower levels of growth stresses, and increased production of mature timber.

Eucalyptus trees tend to exhibit higher wood density values when grown at low densities (DeBell et al. 2001; Espinoza et al. 2009; Malan and Hoon 1992) but this response is not consistent (Goulart et al. 2003; Trevisan et al. 2007). Trees with higher basic densities are associated with quality wood for solid wood products because basic density affects wood properties such as stiffness, hardness, modulus of elasticity, and modulus of rupture (Dickson et al. 2003). Thus, if standard trees respond to increased growing space with higher wood density values, higher quality logs can be produced.

The low densities of residual trees after the first harvest of the stand enables the remaining standard trees to develop large, symmetrical crowns. Eucalypts that grow with symmetrical crowns are less likely to develop elevated growth stresses (Biechele et al. 2009; Touza Vázquez 2001). Growth stresses

released during tree felling and crosscutting logs can lead to log-end splitting (Valencia et al. 2011).

Touza Vázquez (2001) showed that selective thinnings that prioritizes adequate spacing of residual trees can reduce longitudinal growth strains (a proxy for growth stress) up to 60% when compared to row thinnings. This author identified three patterns of longitudinal growth strain formation for *E. globulus* trees (Fig. 1).

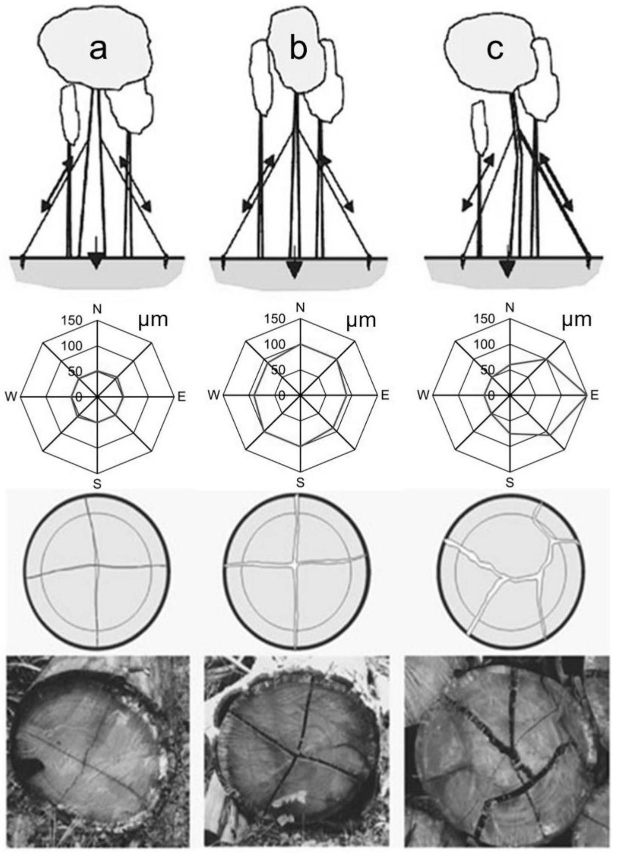

Fig. 1: Relation between *Eucalyptus* growth, distribution of longitudinal growth strains (μm) and log end splitting, where: a) tree growing without crown lateral restriction, b) tree growing with symmetrical crown lateral restriction, c) tree growing with unsymmetrical crown lateral restriction. Adapted from Touza Vázquez (2001), reprinted with permission from CIS-Madera

The tree represented in Fig. 1a grows in an environment of low competition. Thus, crown development is symmetrical and stem bending caused by the wind is reduced due to greater dimensional stability. Growth stresses develop at low intensity, causing little or no splitting when the tree is cut.

In Fig. 1b the tree grows in an environment of strong competition, but evenly on all sides. In this case, the tree develops a small crown and small stem diameter, rendering it unstable and severely affected by wind sway. The longitudinal growth strains are evenly distributed, but occur at high levels in order to stabilize the tree. When cut, the stress between the center and periphery of the log is released immediately, causing deep cracks.

The tree represented in Fig. 1c is affected by environmental conditions forcing the development of an asymmetrical crown. The tree reacts with formation of tension wood on the opposite side. This uneven distribution of the crown results in intense growth stresses that can cause deep asymmetrical end splits when the tree is cut.

Thus, a standard tree will first grow with a small crown, and since the initial diameter increment is reduced (due to tree competition), the growth strains associated with the small crown will be concentrated in a smaller inner section of the stem. Once the standard trees are liberated, the development of large crowns will reduce growth stress rates and produce more stable wood.

Juvenile wood possesses less desirable wood properties than mature wood. It is formed during the earlier growth stages of the tree (around 3 years) in the central core of the stem and also produced in the stem within the living crown or in proximity to physiological processes emanating from the living crown (Larson et al. 2001). The reduction of initial diameter increment coupled with a high green crown height will ensure that standard trees produce logs with large portions of mature wood, limiting juvenile wood formation to a small inner core.

Kojima et al. (2009) reported that the transition between juvenile and mature wood formation for South American *E. grandis* plantations depends, among other factors, on the proximity of the stand to the equator. Xylem maturation in stands near the equator starts when tree bole diameters exceed a given minimum (around 40 cm). Stands planted further from the equator at latitudes less than 18°S start xylem maturation at a given age (9 to 14 years), regardless of tree growth rates.

It can be inferred that high quality logs can be produced from *Eucalyptus* trees managed under the CWS system. The reduced diameter increment of standard trees prior to the first harvest means that juvenile wood will be confined mainly to a small inner core. After the first harvest, standard trees will approach the age to begin producing a transition zone between juvenile and mature wood. Subsequent development of large symmetrical crowns results in lower growth stress development and production of high-quality logs for solid-wood products (Biechele et al. 2009).

Pruning

Eucalypts are self-pruning trees and can be relied on to produce high-quality logs in native forests, where rotations are long and densities high (Kearney et al. 2007). *Eucalyptus* plantations for solid-wood products are managed on shorter rotations. On short rotations self-pruning does not guarantee clear wood production because dead branches are not always shed from the tree (Pinkard and Beadle 1998). These unshed dead branches are dragged through the stem as radial growth occurs, creating kino veins (Eyles and Mohammed 2003).

To ensure production of high-value clear wood from standard trees, early pruning is required. Table 2 shows a common pruning regime for intensively managed South American *Eucalyptus* stands. This pruning regime is applied to stands established at

low densities (620 trees/ha), where the first pruning is combined with thinning to waste down to 450 to 500 remaining trees/ha. The first pruning is completed early to ensure that mostly live branches with small diameters are pruned. Pruning dead branches may create loose knots and increase susceptibility to decay, while inefficient branch stub ejection may create kino traces through the log (Smith et al. 2006). Pruning small branches also reduces the chance of decay spreading into the stem from pruned branches and a maximum allowable branch diameter of 30 mm is recommended for *E. nitens* pruning (Wardlaw and Neilsen 1999).

Table 2: Example of a commercial pruning regime for intensively managed *Eucalyptus* plantations in South America, after Azúa (2003) and Maestri (2003)

Pruning	Age (years)	Pruned height (m)	Pruned trees/ha
First	1.5	3 - 4	450 – 500
Second	2.5	6 - 7.5	300 – 350
Third	3 - 4	9 - 10.3	250

Green pruning (pruning of live branches) accelerates pruning wound occlusion, maximizing clear wood production. Programming pruning to begin with canopy closure is ideal for quality wood production as well as wood growth because after canopy closure the lower branches are shaded and contribute little carbon to the tree (Montagu et al. 2003).

Pruning under CWS management can differ from the regime presented in Table 2 in two respects: (1) the scheduling of pruning and (2) fewer numbers of pruned trees/ha. Initial spacing affects the length of time required for canopy closure: canopy closure occurs earlier in higher density stands (Ryan et al. 2004). Within limits, pruning effects on the growth of unthinned stands are less pronounced than on thinned stands because the foliage removed is shaded and inefficient in terms of carbon sequestration (Forrester and Baker 2012). Thus, pruning in a CWS system should coincide with canopy closure (to avoid pruning dead branches), allowing the removal of 40% to 50% of the green crown length before growth is affected (Forrester et al. 2010).

Since trees harvested in the first cut will be used primarily for biomass energy and pulp production, pruning should be restricted to standard trees only. Selection of standard trees for pruning must be completed prior to the first pruning. Selection criteria typically include dominance (a proxy for vigor), stem form, and evidence of bole defects (Smith and Brennan 2006), as well as a homogeneous distribution in the stand. Since a reduction in growth after pruning may result in a loss of dominance in the pruned trees in relation to unpruned trees (Montagu et al. 2003), care must be taken to avoid removing excessive amounts of green crown when pruning.

Non-timber resource values

Recent changes in forest management perspectives have led to a shift from the sole purpose of timber production to the development of multifunctional forests and the structural diversification of stands, incorporating recreational needs and nature conservation into traditional forest management (Lassauce et al. 2012; Wohlgemuth et al. 2002). Coppice-with-standards might be better suited than high forest or simple coppice systems to maintenance of non-timber resource values. Coppice woods with standard trees are generally richer in wildlife than those without (Fuller and Warren 1993). Standard trees create an additional stratum of vegetation which provides important habitat for many insects and birds. Standard trees can also be a source of dead wood production for the stand. Woody debris in a stand is important to maintain saproxylic insect diversity (Lassauce et al. 2012).

Understory plant regeneration may also be more diverse under CWS stands. Decocq et al. (2004) found a richer and more functionally diverse understory in a temperate deciduous forest managed under a CWS system as compared to that under a close-to-nature selective cutting system.

All the above results were reported from the more traditional CWS plantations of European countries. A recent study in the Brazilian Atlantic forest indicated that 7 year *Eucalyptus* monocultures exhibited moderate capacity to harbor species of the native forest fauna (leaf litter organisms, Rocha et al. 2013). Similar research is warranted for *Eucalyptus* plantation forests managed under the CWS system because increased structural complexity within monocultures may enhance fauna conservation in plantations (Lindenmayer and Hobbs 2004).

Worldwide experiences with *Eucalyptus* under CWS system

Eucalyptus plantations have been managed to some extent under the CWS system in South African countries. *E. grandis* stands were managed by the CWS system in Zimbabwe and Malawi for the supply of transmission and building poles, posts, and fuelwood. In these plantations, 50 to 200 standards were retained after the first harvest at 5 to 7 years, with the final harvest of the remaining stand at 12 years (Poynton 1983).

Recent research concerning the management of *E. globulus* for the production of quality solid wood products in northwestern Spain under short rotations has taken note of the possibility of application of the CWS system (Nutto and Touza Vázquez 2004). This regime is composed of an initial planting density of 1111 trees/ha, followed by two thinnings (at 6 and 11 years) down to 530 and 130 trees/ha, respectively. The whole stand is cut by age 26 years (or later), guaranteeing large diameter standard trees for solid wood products as well as 100 m^3/ha of additional wood from the coppice growth for pulping.

Reynders (1984) studied the species *E. saligna* and *E. maidenii* managed under simple coppice, CWS, and high forest systems in eastern Africa (Rwanda and Burundi). The experiment was carried out in stands with initial density of 4444 trees/ha at 5 years of age, composed of seven treatments: clearcutting, keeping 6 different intensities of standard trees in the stand (100, 150, 200, 250 and 350 to 400 trees/ha), and thinned to about 2000

trees/ha (Fig. 2a and b). Total production volumes of the different treatments were similar. Only two treatments, clearcutting and thinning to ±2000 trees/ha, were statistically different. This lack of significant difference allows the manager great freedom of action. Reynders (1984) recommended the application of the CWS system by cutting the coppice growth and some standard trees every 5 years, to reach a final density of 50 standard trees/ha. As for the remaining density of the standard trees, a low intensity CWS system (between 100 and 250 trees/ha) enables the coppice wood to reach appropriate commercial size between cut periods (every 5 years) and enables high growth increments for the standard trees. For the system practiced at high intensity (up to 400 trees/ha) greater importance is given to the standard trees, making the coppice production of secondary importance. Fig. 2 shows productivity of various *Eucalyptus* species managed under the CWS system in Africa (Fig. 2a and b) and Brazil (Fig. 2c and d).

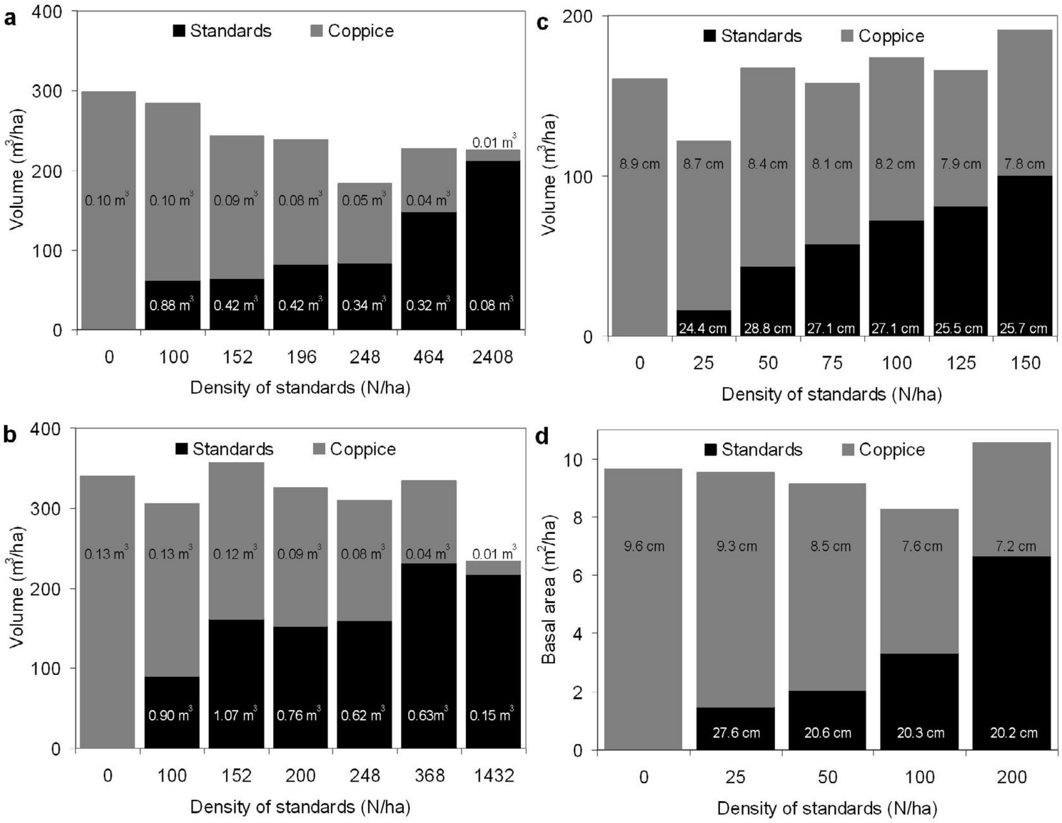

Fig. 2: Standing wood volume per hectare at age 10 for *Eucalyptus maidenii* (a), *E. saligna* (b), at age 13 for *E. saligna* (c) and standing basal area at age 11 for *E. grandis* (d) managed under the CWS system, contrasting production from standard and coppice trees. Data based on Inoue and Stöhr (1991), Reynders (1984), and Spina-França (1989).

Note: The numbers in columns of Fig. 2 represent the average volume per tree for the standards and average volume per stump for (a) and (b), average diameter per standard tree and per sprout for (c) and average diameter per standard tree and per stump for (d). The differences in productivity between the Brazilian and African sites are mainly due to initial spacing density, of circa 1800 trees/ha for the former and 4444 trees/ha for the later.

Two trials of *Eucalyptus* managed as CWS system in south-eastern Brazil were reported, one by Spina-França (1989) with *E. camaldulensis* (evaluated 5 years after the first cut of an 8 year-old stand, Fig. 2c), and one by Inoue and Stöhr (1991) with *E. grandis* (evaluated 4 years after the first cut of a 7 year-old stand, Fig. 2d). Both studies conducted the coppice with two to three sprouts per stump.

Particularly for *E. saligna*, five years after the first cut Spina-França (1989) reported that standard trees did not influence survival, average height, or dominant height of the sprouts; standard trees did influence the development of quadratic mean diameter of the sprouts; and there was no competition between standard trees. For reasons unexplained by the author, the standard trees in the CWS with the lowest density (25 trees/ha) did not yield the highest diameter gain. This might have been due to a micro-site problem, since this treatment presented the highest stump mortality of all, 38% versus an average of 19% for the other treatments. The author did not recommend that *E. saligna* be managed under the CWS system, stating that amount of wood loss caused by not cutting the standard trees and the competition to the coppice understory as the main reasons.

Considering *E. grandis*, Inoue and Stöhr (1991) reported that when wood prices are not differentiated by log size, simple coppice was more profitable than the CWS system for standard densities ranging from 25 to 200 trees/ha. However, when logs from the standard trees attain prices 1.4 times greater than the coppice

wood, the CWS system with a density of 25 trees/ha was the most profitable regime. For selling prices 3 times greater, the CWS system with a density of 200 trees/ha became the most profitable regime. Standard trees planted at the lowest density (25 trees/ha) recorded the greatest increments in post-coppice diameter growth, with values 34% higher than the next lowest density. This showed the growth capacity of *E. grandis* when freed from competition.

Potential application of *Eucalyptus* under the CWS system

The sprouting capacity and large dimensions attained by many *Eucalyptus* species make them excellent candidates for a two layer CWS system. The few published reports of eucalypts managed under this system have not included long term measurements and the longest term of study was 13 years. It can not be ruled out that the CWS management scheme is more profitable than clear cutting followed by coppice management when the standards are allowed to grow for three or more cycles (a rotation of 21 years considering a 7 year cycle), provided that higher prices are paid for large diameter wood. Long term research plots are needed to quantify wood production and quality under this scenario.

The adoption of the CWS system for *Eucalyptus* will require a trade-off between producing the maximum amount of coppice wood from a stand (e.g. clear cutting followed by a simple coppice crop) and producing the maximum amount of sawlog wood (e.g. application of a moderate thinning without consideration to the coppice understory). Thus, finding the ideal compromise between standard tree density and coppice growth is important for the success of the management of *Eucalyptus* under the CWS system.

Appropriate sites must be selected for the application of CWS because resource availability (nutrients, light, and water) can change the competition dynamics between the coppice and standard trees. Forrester et al. (2003) found that 2 to 3 years after thinning *Eucalyptus sieberi* stands, the proportion of total stand basal area occupied by coppice shoots increased with thinning intensity (reaching up to 33% of total stand basal area). However, this relation was stronger on lower quality sites than on medium or high quality sites, with coppice basal area much lower in higher quality sites than in stands of lower site quality. Site climate will also play an important role with regard to stump mortality due to fungal pathogens. Areas that are prone to fungal attacks (such as high temperatures and humidity areas) will incapacitate the formation of the coppice crop and should be avoided for a CWS system.

The ability of the species to grow a coppice crop under a tree canopy plays an important role in the application of the system (Fig. 3), since a high density of standard trees can impose elevated competition on the coppice crop. The performance of the coppice component in relation to the density of standard trees is shown in Fig. 3. *E. grandis* produced 78% of the amount of coppice wood at 25 trees/ha standard density when compared to a simple coppice stand. These values drop to about 40% when the density of the standards was raised to 100 trees/ha. This indicates that the coppice component suffered from light competition when the density of the standards was too high. In contrast, *E. maidenii* produced about 75% of coppice wood when grown at a standard density of 100 trees/ha, indicating a greater shade tolerance than *E. grandis*.

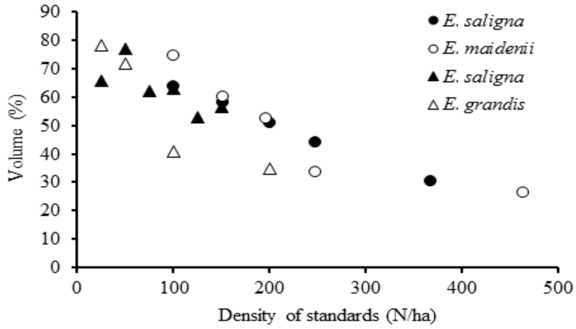

Fig. 3: Influence of standard tree density per hectare on amount of coppice wood volume production compared to simple coppicing. Triangles represent Brazilian sites and circles represent African sites. Data based on Inoue and Stöhr (1991), Reynders (1984), and Spina-França (1989)

A key component of the CWS system is the diversity of products obtained from the stand. To benefit from this diversification, the forest must be situated within economical transport distance to small-scale timber markets. Since large-scale timber can be sold at premium prices, it can support longer transport distances. Even greater diversification of products can be achieved in the CWS system if an essential oil producing *Eucalyptus* species is used. This way, leaf production can also be sold at the moment of wood harvest. Common oil yielding *Eucalyptus* species include: *E. citriodora* (currently *Corymbia citriodora*), *E. globulus*, *E. polybractea*, and *E. camaldulensis* (Batish et al. 2008).

E. critriodora is an ideal candidate for management by the CWS system. The species presents high basic density wood, with values ranging from 790 to 910 kg/m^3 (Almeida et al. 2010; Néri et al. 2000). High wood density indicates that the species is suitable for charcoal as well as solid wood production. *E. critriodora* can reach large diameters if grown at low densities, even when late thinnings are applied (Aguiar et al. 1995).

Thus, the growth, wood properties, and essential oil production of *E. critriodora* can result in successful management of the species under the CWS system, especially if conducted in high charcoal consuming areas. While studies claim that *E. critriodora* possesses good sprouting potential (Andrade 1961; Ferrari et al. 2004), some authors have reported problems with sprouting capacity (Higa and Sturion 1991; Webb et al. 1984). Silveira et al. (2000) indicated that the sprout growth of the species is linked to the nutrient status of the plants. In this sense, fertilizer application around the time of harvest, as well as amelioration of the many factors that can negatively influence coppice regeneration (Table 1), are important to ensure the successful management of *E. critriodora* under the CWS system.

An example of a suitable area for the management of *Eucalyptus* under the CWS system is Minas Gerais State, Brazil. Due to its large, charcoal-based steel industry, Minas Gerais State is the largest consumer of *Eucalyptus* charcoal in Brazil, consuming 81% of a total national consumption of 3.5 million tons in 2010. This State was also responsible for the production of 40% of approximately 10 thousand tons of the nation's *Eucalyptus* leaf production used for essential oil extraction in 2010 (IBGE 2011). As for the solid wood products market, the State houses the third largest furniture industry of the country (Pires et al. 2008), with many companies using *Eucalyptus* wood as raw material (Teixeira et al. 2009). The combination of diverse markets and the current 1.4 million hectares of *Eucalyptus* plantations in Minas Gerais (ABRAF 2012) make it a potential site for small and medium forest owners to diversify forest production using the CWS system.

Recommended management regime for *Eucalyptus* in CWS system

An outline for the silvicultural management of *Eucalyptus* under the CWS system is presented in Table 3. It is important to note that this scheme will vary according to site and species characteristics.

Table 3: Outline of the main silvicultural operations to be applied in *Eucalyptus* stands managed under the CWS system considering two different initial planting densities

1st rotation	Pruning (year)	1st cut (year)	Remaining standards (trees/ha)
High density (2 × 2 m)	1–2	5.5–7.5	25–100, depending on objective
Low density (4 × 3 m)	1.5–2.5	6.5–8.5	
	Stump thinning (Months)	Number of sprouts (Sprouts/stump)	Coppice cut (year)
Coppice management	6 – 9 after cut	1–3, depending on objective	7, 6 or 5 years after harvest for 1, 2 and 3 sprouts/stump, respectively

The first silvicultural operation that must be conducted on the standard trees is live crown pruning. The appropriate time to conduct this operation is upon canopy closure, which varies with species, site and planting density. The growth rate of the trees will also determine the appropriate time for the first harvest, with higher productivity sites, and higher initial densities, requiring earlier intervention. The number of standard trees to remain in the stand will depend upon the desired target diameter of these trees and the importance given to the coppice production. If high coppice yield coupled with large diameter standard trees is desired, then densities can be low for standard trees (e.g. 25 to 50 trees/ha).

Fertilizer applications to replace nutrients removed during harvest might be helpful to guarantee successful growth of the coppice understory (Connell et al. 2004, Gonçalves et al. 2008). A sprout thinning operation can be conducted to avoid excessive competition between sprouts. The number of sprouts per stump will determine the size of final coppice production as well as the age of subsequent coppice harvests. For instance, leaving three sprouts per stump will result in small wood for energy and early harvest to avoid growth stagnation of the coppice wood growth.

The number of coppice cycles before the harvest of the standard trees will be determined by the target diameter and density for standard trees. For example, a low initial planting density followed by two to three coppice harvests leaving one sprout per stump will allow the standard trees to grow during a 21 to 28 year rotation (Table 3). This long rotation of the standard trees will ensure large diameter logs with abundant production of mature wood. The advanced age and possible damage to the remaining stumps may require replanting the entire stand after the standard trees are harvested.

Acknowledgments
The authors are grateful to Andressa Ribeiro and Joseph Catalano for comments and revision of the text. Comments by two anonymous reviewers helped improve the original manuscript.

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